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Title: MaRIE XFEL Pre-Conceptual Reference Design Injector

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Intended for: This presentation was originally for a private meeting regarding the MaRIE facility. We would like to make it more widely available.

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MaRIE XFEL Pre-Conceptual Reference Design Injector

Steve Russell, Bruce Carlsten, Leanne Duffy, Frank Krawczyk, John Lewellen and Rich Sheffield

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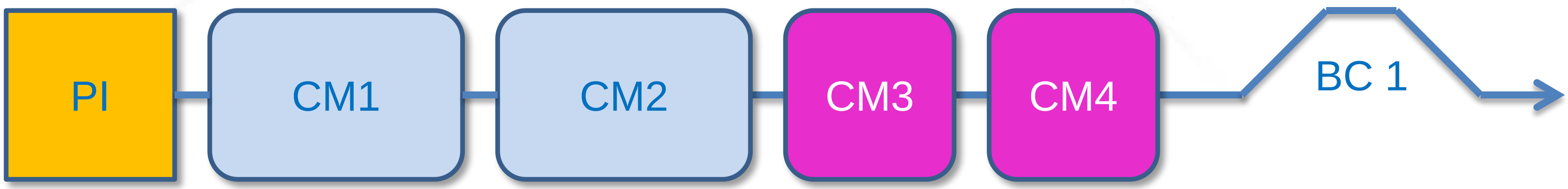
Outline

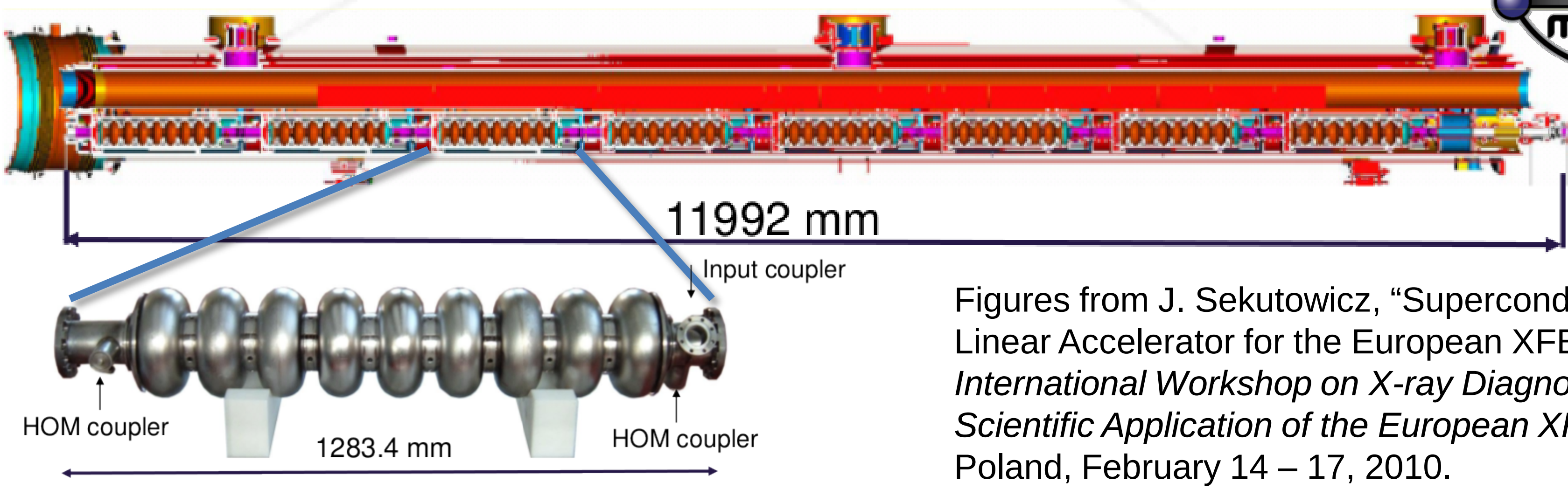
- Injector region defined.
- Description of accelerating cryomodules.
- Current photoinjector concept and motivation.
- Discussion of bunch compression will be in the next talk.
- Risks and needed R&D.

Injector region defined



- Photoinjector (PI)
  - 1.3 GHz, normal conducting.
  - Long pulse (100 μs) operation, 60 MV/m gradient at cathode.
- Cryomodules 1 & 2 (CM1 & CM2)
  - 1.3 GHz superconducting.
  - Capture beam from PI, accelerate and introduce energy slew for BC1.
- Cryomodules 3 & 4 (CM3 & CM4)
  - 3.9 GHz superconducting.
  - Linearize beam energy slew for BC1.
- Bunch compressor 1 (BC1)
  - ~ 20x compression at ~ 400 MeV.

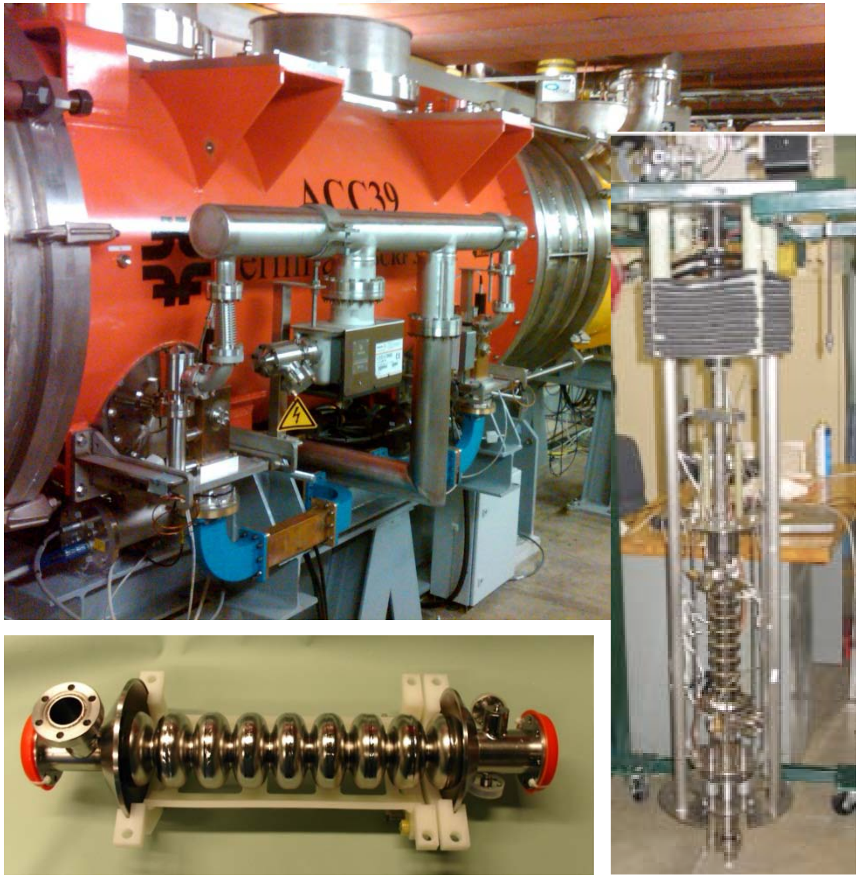
1.3 GHz cryomodule



Figures from J. Sekutowicz, “Superconducting Linear Accelerator for the European XFEL”, *International Workshop on X-ray Diagnostics and Scientific Application of the European XFEL*, Ryn Poland, February 14 – 17, 2010.

- 1.3 GHz cryomodule has slots for 9, 9 cell accelerating cavities.
  - Type A
    - All 9 slots filled with accelerating cavities.
    - Injector uses Type A cryomodules in present concept.
    - CM1 has independent phase and amplitude control for each cavity. (This allows for more efficient use of CM1, but may not be strictly necessary.)
  - Type B
    - 8 slots filled with accelerating cavities.
    - One slot reserved for a quad/BPM/steering magnet.

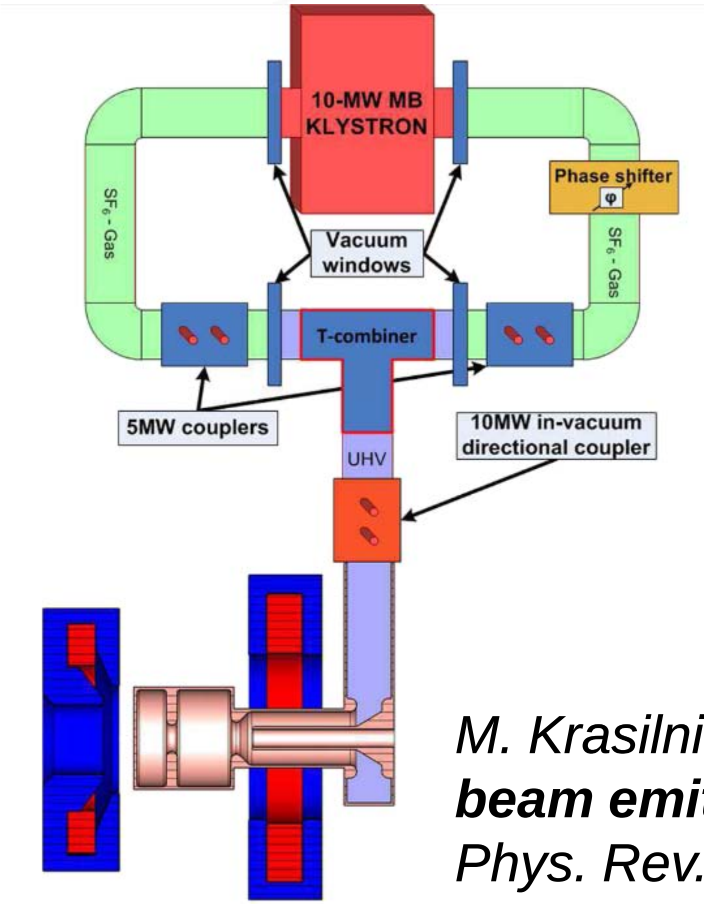
3.9 GHz cryomodule

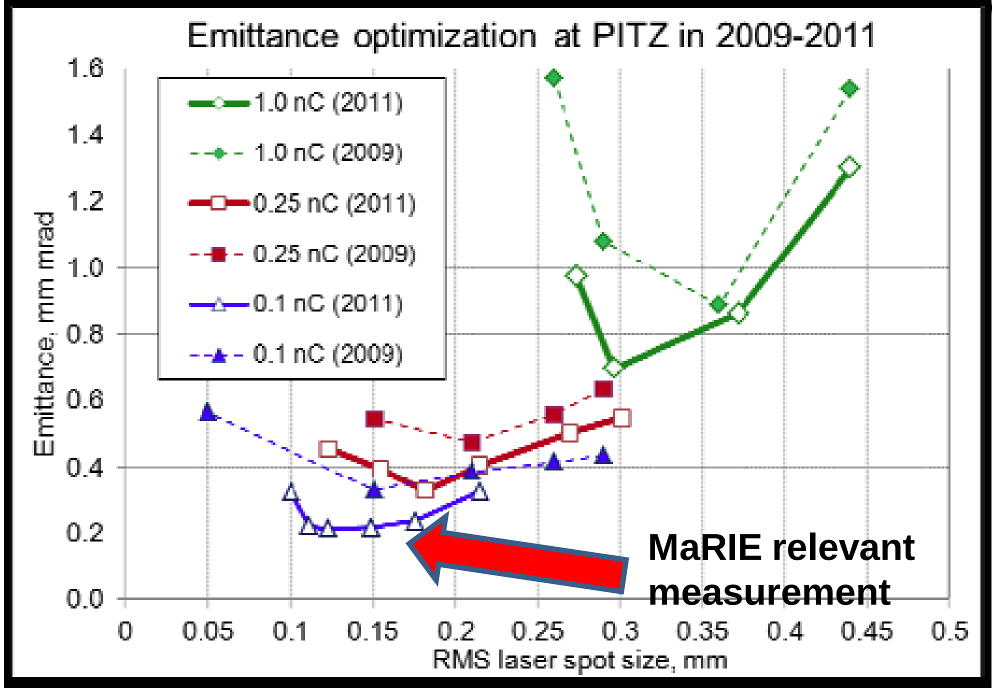


- Cryomodules contain 4 accelerating cavities.
- Accelerating cavity scaled from 1.3 GHz cavity.
- Routine operation at FLASH with 18.9 to 19.7 MV/m average gradient.
- Capable of 22 MV/m average gradient.
- Fabricated by FNAL.

E. Harms, “3.9 GHz Cryomodule for FLASH”, *FNAL-LBNL joint meeting on SRF Cavities and Cryomodules*, March 25, 2012.

PITZ results from 2011 motivated our choice of photoinjector design



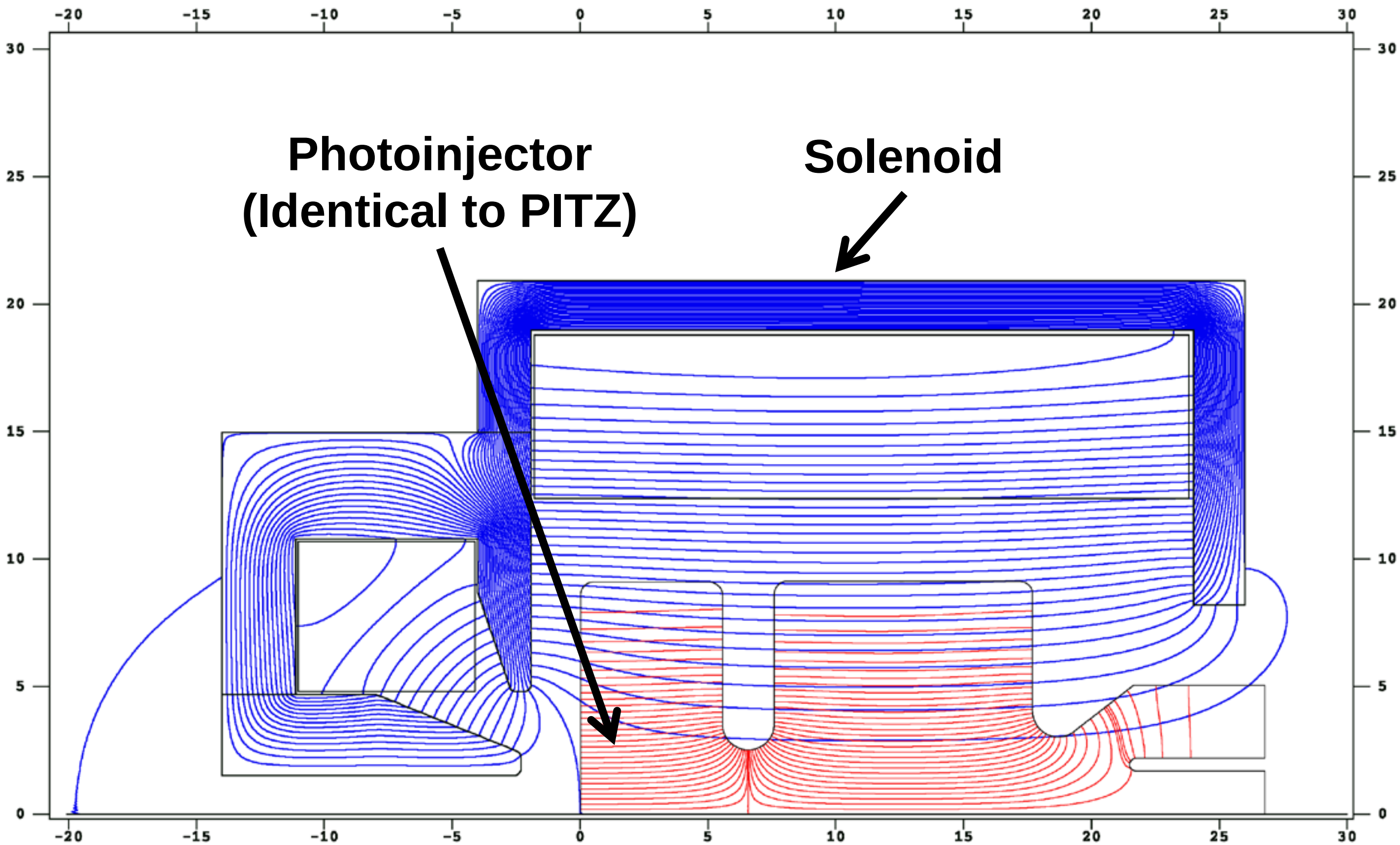


*M. Krasilnikov, et. al., **Experimentally minimized beam emittance from an L-band photoinjector**, Phys. Rev. STAB, **15,** 100701 (2012).*

PITZ has demonstrated several key technologies need by MaRIE

- Reliable operation at long RF pulse length (100s of μs) at high gradient (60 MV/m).
- Long RF pulse length with low dark current.
  - Dry-ice sublimation-impulse cleaning method.
  - <200 μA with 200 μs RF pulse at 60 MV/m (Igor Isaev, *Unwanted Beam Workshop 2012*, Humbolt-University Berlin, December 17 – 18, 2012).
- MaRIE relevant emittance values.
  - Our XFEL assume the 0.1 nC and 0.2 μm normalized slice emittance measured by PITZ.
- But can we do better?

MaRIE photoinjector and solenoid (current concept)



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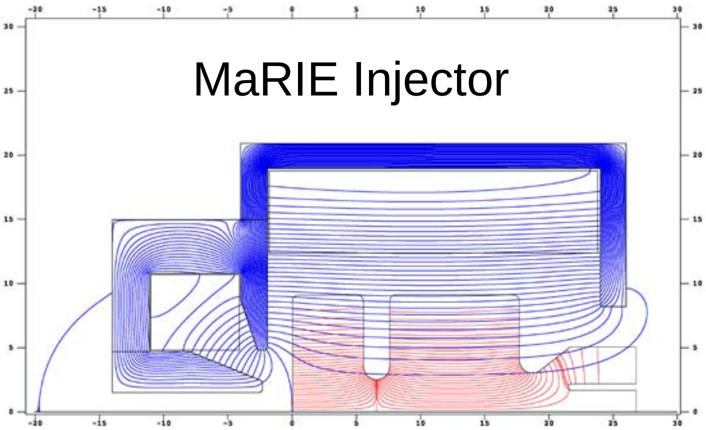
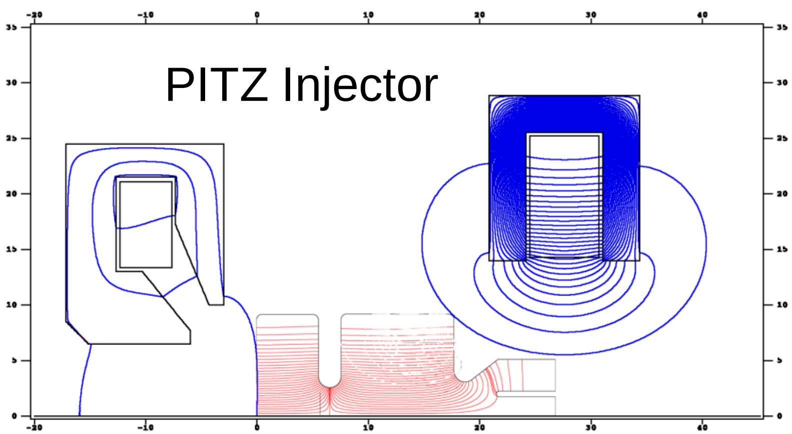
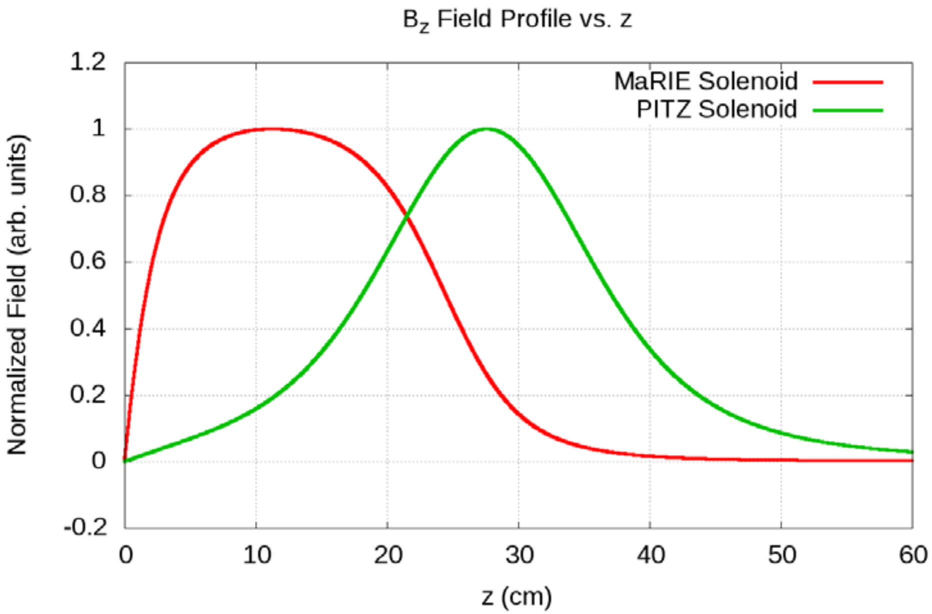
The “key” difference is the solenoid

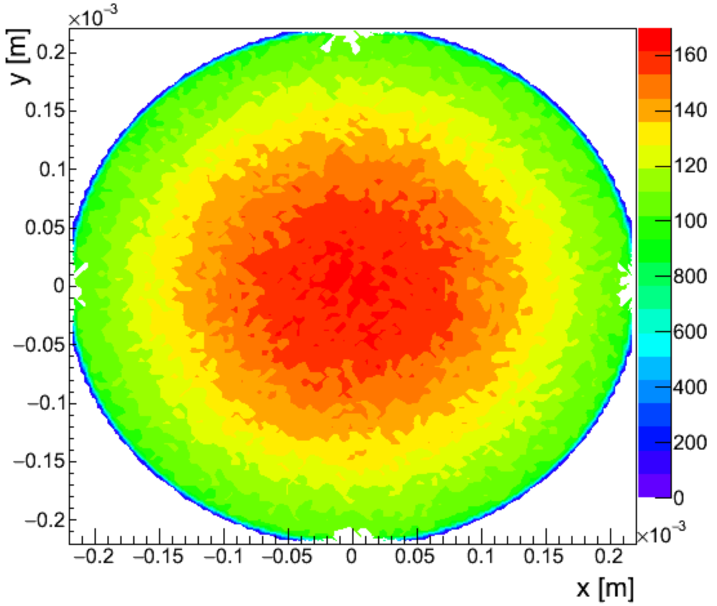




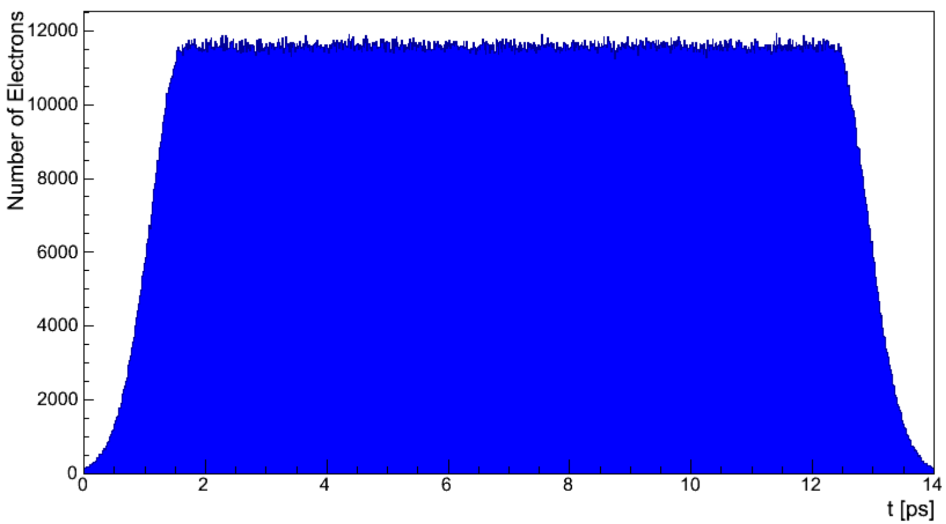


Simulated beam emission profile (point design)

Emission Spot on Cathode

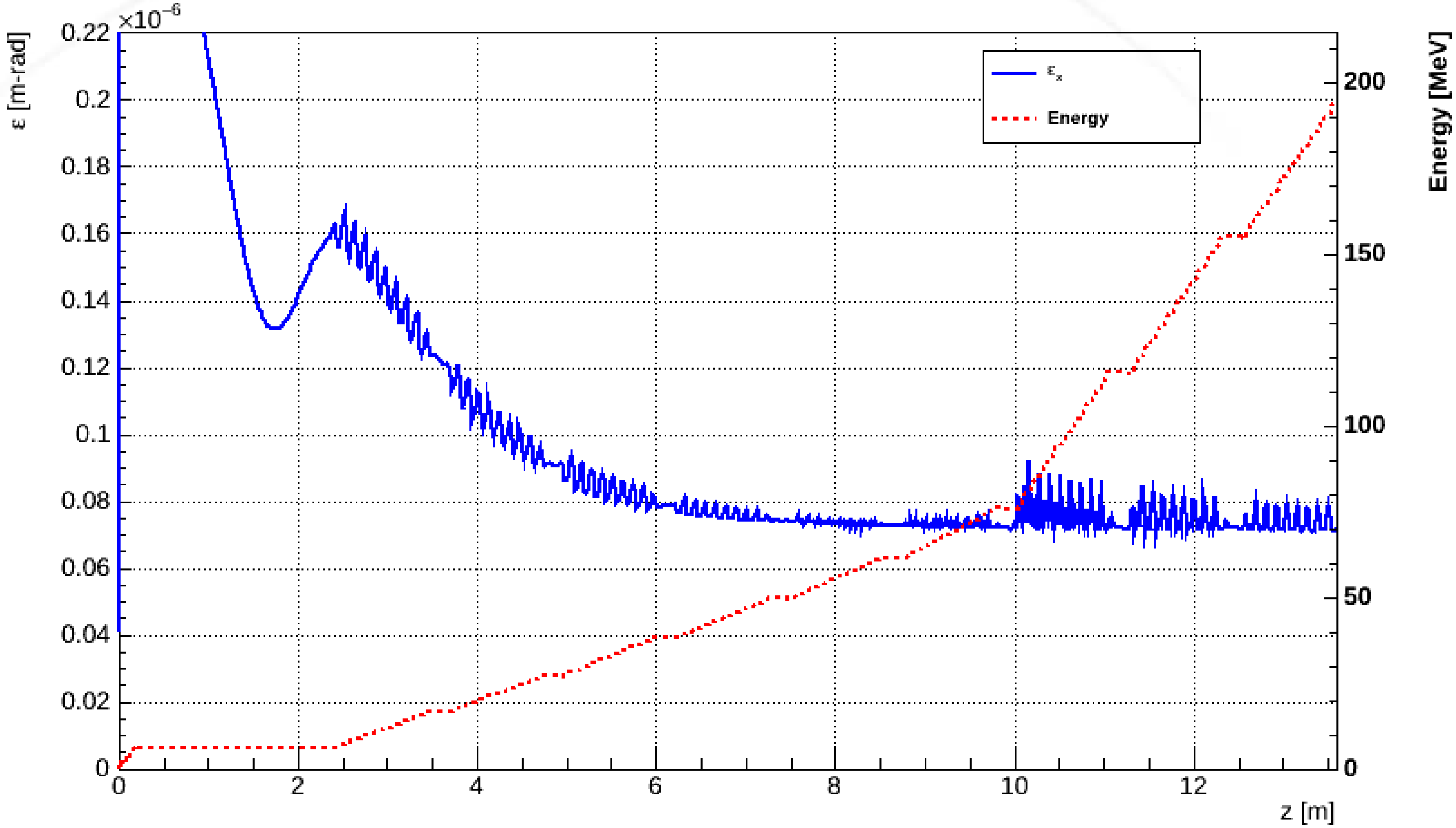


Longitudinal Emission Profile



Beam emission spot and longitudinal profile from photocathode in OPAL point design simulation. The transverse profile is a “cut Gaussian”. (i.e. a Gaussian distribution with aperture at a radius of 1 σ.)

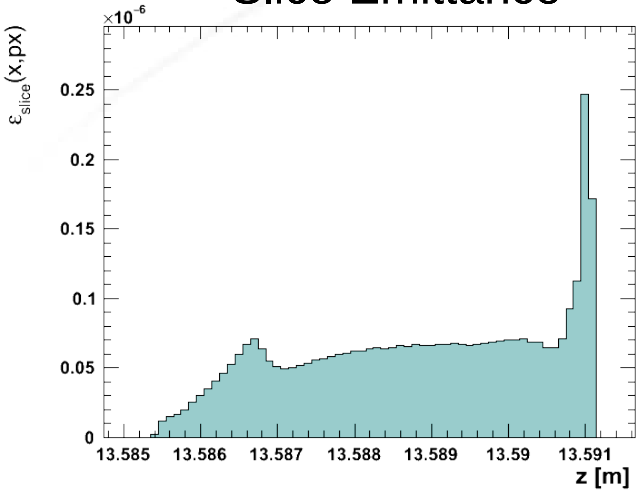
Beam energy and emittance through first cryomodule



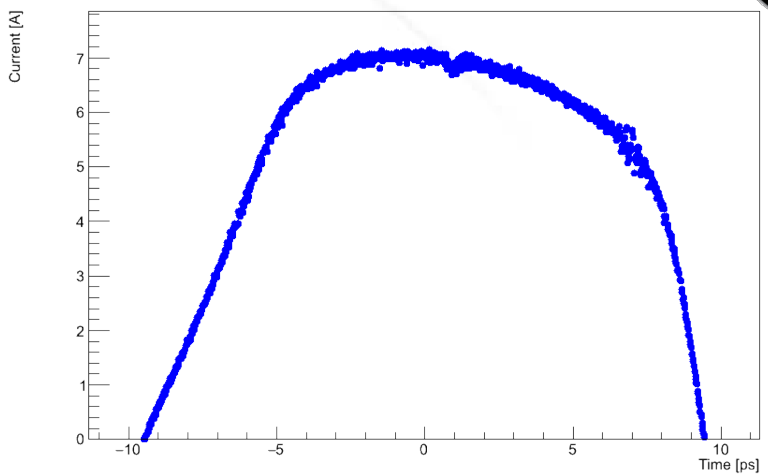
Optimization for 100 pC/bunch charge using 10M particle OPAL runs (Object oriented Particle Accelerator Library, https://amas.psi.ch/OPAL/wiki)

Beam properties prior to CM2

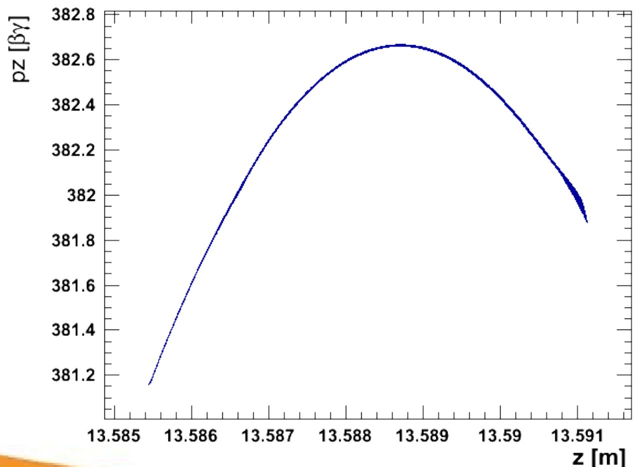
Slice Emittance



Current vs. Time



Longitudinal Phase Space



Property	Value
Energy	195 MeV
Charge	100 pC
Transverse RMS ε_n	73 nm
Thermal ε_n (copper)	41 nm
Residual ε_n	60 nm
RMS Length	5.5 ps
RMS Energy Spread	0.08%

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Photocathode assumptions

- Simulations assume copper cathode.

- Thermal emittance calculated using model from Dowell and Schmerge (D. Dowell and J. F. Schmerge, *Phys. Rev. STAB*, **12**, 074291 (2009)).

- Recent results from the SwissFEL show measured thermal emittance in agreement with theory (E. Prat, et. al., *Proceedings of the 2014 Free Electron Laser Conference*, August 25 – 29, 2014, Basel, Switzerland, THC02.)

Summary – Risk Table

Item	Severity	Risk reduction path
Injector model incomplete	Medium / High	Include 3D structure effects, short range wakes, BC1 (with CSR) etc. Confidence in injector emittance is tentative until all known physics are included.
General numerical studies	Medium	Lots of simulations: • Explore the injector parameter space to find “optimal” beam solution. • Do real world (600M particle) simulations to understand beam noise effects. • Trade and sensitivity studies.

Summary – Risk Table

Item	Severity	Risk reduction path
Long range wakes	Medium	Numerical and experimental study. Long range wake effects will determine minimum electron beam spacing.
Photocathode preparation	Medium	Understand copper photocathode preparation to achieve demonstrated state-of-the art thermal emittance and desired emission profile.

Summary – Risk Table

Item	Severity	Risk reduction path
New photocathode material	Low	Implement improved photocathode numerical models. Experimental studies of semi-conductor cathodes. Photocathode is low risk as we have a solution, but a better photocathode could reduce risk elsewhere. For example: Lower thermal emittance ➔ Larger emission spot radius ➔ Shorter beam bunch from photoinjector ➔ Less beam compression

Summary – Risk Table

Item	Severity	Risk reduction path
Demonstrated injector performance	High	Experimental demonstration of the injector performance using the MaRIE Injector Test Stand (MITS). This experiment will be a critical milestone on the path to MaRIE.

Charge Question 1

1. Evaluate our current reference design as it stands and identify its key technology weaknesses and highest risk aspects.

   The design is incomplete, but early results indicate that we can meet crucial beam quality requirements from the injector. Our model is missing key physics whose impact we have yet to assess. In particular, we need to carry the simulation through the first bunch compressor with a real world number of particles and demonstrate emittance preservation during beam compression.

   a. Is this pre-conceptual point design for the linac system, including the RF parameters, choice of SC structures, charge and emittance logical and feasible?

      For the injector the answer is yes. I will defer the assessment of the rest of the linac systems to the talk by John Lewellen.

   b. Is this pre-conceptual point design for the X-FEL, including the energy and number of photons, logical and feasible?

      I defer to Dinh Nguyen's talk and conclusion for this.

Charge Question 2

2. Evaluate state-of-the-art, conventional XFEL technology and identify critical shortcomings based on the MaRIE XFEL requirements. Identify the highest science and engineering risks that must be retired with R&D to enable us to design and build the MaRIE XFEL.

   Our injector design is only a slight modification of what has been done, and it relies only on demonstrated conventional technology. That being said, the improvement in performance (slice emittance and slice energy spread) we are proposing is not trivial and so experimental validation is critical. Fortunately, the required R&D is straightforward and can be done with a modest (relative to the full MaRIE) facility.

Conclusion

- Our initial results are promising, but there is lots of numerical work still to do.
- Crucial performance parameters (e.g. photocathode thermal emittance) have already been ***experimentally*** demonstrated.
- The key experiment will be injector beam quality demonstration with MITS.